APPENDIX H
Materials Science and Processing in Space

INTRODUCTION

An Earth-orbiting manned space station will provide important new capabilities for the pursuit of research and development activities in the general field of materials technology. The availability of skilled men who can function in the space station allows for radically different designs from those required for unmanned space experiments. It can result in lower experimental costs, broader flexibility in experimental objectives, increased experimental reliability, and longer useful lifetimes for the experiments. In the areas with which this paper is concerned, so little is known about the unique effects of the space environment that many of the experiments must be heuristic in nature, and it is in precisely this milieu that man is most useful.

Despite the great importance of materials technology and the enormous amount of research devoted to the subject, a systematic program for carrying out such research in space has received relatively little study. A number of general qualitative surveys have been presented at meetings devoted to practical space applications (refs. 1 to 3), and proposals have been made for individual experiments in such related fields as physics, advanced technology, and engineering operations. Recently, however, Marshall Space Flight Center has initiated a program to identify and evaluate candidate processes for space manufacturing (refs. 4 to 6). These efforts have been primarily directed toward applications, but extensive research is clearly required before specific products can be developed.

Our objective in the following sections is to discuss the most promising new processes and materials and to make a preliminary

evaluation of their future potential. At present, we can only speculate on what the eventual applications will be.

PROPERTIES OF THE SPACE ENVIRONMENT RELEVANT TO MATERIALS AND PROCESSING

We will first consider the properties of the environment that may lead to new processes and applications. In this respect, the one unique characteristic is the phenomenon of weightlessness, usually referred to as zero-g. This is the only factor that cannot be duplicated on Earth, although such features as the large volume of vacuum may remain difficult or costly to produce.

THE GRAVITATIONAL FIELD

It is important to recognize that zero-g does not mean literally zero gravitational force in orbit, but rather an approximate balance between the gravitational and centrifugal forces. All free-floating objects have independent orbits and will generally contact a container wall within one orbit, unless an external force is applied to prevent this. Other sources of disturbance include crew motions, mechanical and acoustical vibrations, attitude-control and orbit-keeping maneuvers, and atmospheric drag.

The required constraining force in all cases is quite small and accelerations of 10^{-5} g or less should be maintainable for extended periods of time. Accelerations during peak station maneuvers and crew activities, however, may increase to 10^{-2} g. A more detailed discussion of the zero-g environment is presented in "Limitations on Zero-G" (p. 170); see also "Requirements for a Space Facility" (p. 169).

THE SPACE VACUUM

The level of vacuum in low Earth orbit is considerably poorer than the 10^{-13} to 10^{-14} torr currently achieved in vacuum chambers. For comparison, mean atmospheric pressures for several representative altitudes are given on the next page (ref. 7).

Altitude, km	*Nautical miles*	*Pressure, torr*
150	81	3.8×10^{-6}
300	162	1.4×10^{-10}
700	378	8.9×10^{-12}
> 2500	1350	$< 10^{-12}$

These values are the lower limits on the attainable vacuum pressure, since spacecraft leakage will contaminate the environment. Calculations on predicted leak rates for the Apollo Command module or lunar module indicate that the effective pressures will be as high as 10^{-5} torr within a few meters of the leak source.*

The unlimited vacuum of space can be of significant value where high mass-flow rates are required. Back contamination resulting from low pumping rates and small volumes is often a limiting factor on vacuum chamber performance. This would not be a constraint in free space, so that much larger flow rates could be achieved. Vacuum technology is advancing rapidly, however, and by the time space processes requiring large vacuums become feasible, Earth capabilities for vacuum pumping may be competitive with Earth orbit, both in pumping rates and cost.

The vacuum in the vicinity of an orbiting laboratory does not appear to offer a sufficiently unique capability to provide a circumstance that would justify space manufacture. In conjunction with other properties of an orbiting laboratory, it might prove a useful adjunct.

RADIATION ENVIRONMENT

The high-energy and particle radiation environment does not appear to provide particularly useful characteristics, because fluxes are too low and are subject to random fluctuations. Temperatures on the order of 5000° K, difficult to obtain using normal heat-transfer methods, can be attained with solar reflectors. Again, this would be a useful adjunct rather than a unique capability (ref. 8).

*F. G. Allen of Bellcomm, Inc., private communication, 1968.

OPPORTUNITIES PROVIDED IN ZERO-G

A number of unique processes have been suggested for possible study and application in the space environment. Lists of these processes have been given by Wuenscher (ref. 5), Frost (ref. 9), and Steurer (ref. 10).

In zero-g, density variations become unimportant and convection currents are suppressed. Variable-density mixing of immiscible liquids and liquid/solid/gas suspensions is achievable. Contact between bodies can be eliminated by selective force-field constraints, avoiding introduction of contact distortions and impurities. Vibrations can also be effectively isolated.

It is difficult to gage the potential impact of specific processes for products which would be otherwise unavailable or impractical to manufacture in the Earth environment. Some applications are immediately recognizable, but others, of perhaps more far-reaching consequences, remain yet to be discovered.

The following sections summarize and review the most promising of the processes proposed. Specific applications are cited only as representative examples of potential use.

IMPROVED CRYSTALLOGRAPHIC OR MICROSCOPIC PROPERTIES OF MATERIALS

Levitation by radiofrequency fields on Earth, the closest long-term simulation of zero-g, has shown great promise, but suffers from the basic limitations of being restricted to conducting materials and to small quantities. Moreover, the supporting forces are concentrated near the periphery, where induced eddy currents are maximum. In zero-g, these processes can be extended to nonmetallic substances as well as high-temperature ceramics, as for example, melting of free-floating refractory materials that are subject to contamination when in contact with any crucible or mold. Production of materials with components added in precisely specified amounts or locations, and of very large crystals or crystals free from imperfections, appears feasible. In Earth orbit, semiconductor materials and ceramics could conceivably be refined in amounts limited only by the stability of the liquid melt under surface tension. Achievements in these areas are of considerable scientific interest, and have the promise of practical applications.

Such processes as materials purification, homogenization of alloys having large density differences between phases, preparation of new alloys, semiconductors, and mixed crystals and glasses are also feasible. Ultrahigh-purity glasses, growth of crystals directly from the levitated mass, and solidification involving extreme supercooling are other possibilities. (A characteristic of supercooled material is the formation of extremely small crystal grains, which appears to be the mechanism by which materials achieve superplasticity. Elongations in metals of greater than 1000 percent have been observed (ref. 11).

Floating-zone melting is another process with great potential. Relaxation of present restrictions on the size of the molten zone should permit application of this technique to materials that are not now feasible on Earth. In addition, crystals of much larger diameter could be grown (ref. 12).

Convection currents have been shown to be a source of dislocations and other inhomogeneities in crystals grown from the melt (ref. 13). Suppression of these currents should reduce the number of imperfections. In fact, it may be possible to grow very large dislocation-free crystals from nonmetallic substances. For crystals grown from solution or vapor, the absence of convection would cause the process to become diffusion controlled. As a result, the growth rate would be reduced, allowing greater precision in control of additive components.

The weightless condition could eliminate the need for supports, another major source of imperfections (refs. 9 and 14). Seed crystals could be suspended in the center of the melt, solution, or vapor. The absence of stresses in crystals grown by pulling could allow much larger perfect crystals to be grown by this technique.

Single crystals of high perfection are in great demand for many applications. The technology of crystal growing is an extensive and rapidly growing field, and predictions of the future value of any particular technique are difficult to make. Nevertheless, the weightless environment of space does offer some possible solutions to currently unsolved problems.

NOVEL STRUCTURAL MATERIALS

Entirely new classes of alloys, colloids, and variable-density solids and solid/gas mixtures, utilizing characteristics of the zero-g environment, can readily be conceived. These include high-strength

foams, metallic and nonmetallic mixes, variable-density melts for casting, etc. Other than their utilization as subject materials in basic research, however, it is difficult at this time to assess the benefits derivable from such materials. For example, it may be possible to fabricate high-strength foams and structures by controlled distribution of gas bubbles, but it is not clear that such materials would offer advantages warranting space processing. The problem is not in visualizing new materials, but in establishing justification of their value. The crucial question is whether the quantity returnable to Earth would be worth the cost. The material must be worth a great deal per pound and per cubic foot, and relatively small quantities must satisfy demand. There may be possible uses of such materials *in* space, but at present these do not look as promising as competitive approaches that utilize the assembly of modularized structures.

Particularly promising applications of new structural materials are the high-strength composites, which will now be considered in some detail to illustrate possible benefits derived from zero-g processing.

High strength to weight composite materials are formed by embedding microscopically thin, dislocation-free crystalline whiskers in a matrix or filler material. In practice, bond failure between the whiskers and filler is the governing failure mechanism. Composite material strength can be increased by (1) using longer elements, and (2) achieving optimum whisker spacing and alinement. In the Earth environment, practical problems associated with physical spacing and alinement of whiskers in the matrix material are prohibitive, and are responsible in large measure for the current high costs of composites, which sometimes are thousands of dollars per pound. In zero-g, it may be practical to grow longer whiskers from free-floating droplets and also to alleviate spacing and alinement problems. For example, polarization techniques could be employed to stratify and aline crystals along the desired axes. Matrix material could be vapor-deposited to achieve uniform "wetting" at the bonding interface and maintain uniform spacing and alinement.

FORMING PROCESSES

In the absence of a gravitational field, forces of secondary influence in the Earth environment become of paramount importance. For example, materials in the liquid state rapidly take the

form of perfect spheres under the influence of surface tension. Likewise, spun liquid masses form accurate ellipsoidal shapes.

Numerous forming processes that depend on the lack of convection and the absence of gravity separation and distortion have been proposed (refs. 4, 5, 9, and 10). These include thin-wall membranes and castings, forging and extrusion of long, delicate structural components, blow-molding of complex components, and a variety of casting techniques utilizing materials of differing densities. Some of these processes can have significant use in basic research. Whether markets will develop for products utilizing these processes, however, is uncertain.

A case in point, demonstrating the need for further understanding of these processes, is a suggested method of fabricating hollow ball bearings (ref. 5), a very desirable product under active investigation at the present time, with imperfect results so far. In space, formation of a hollow sphere by injecting gas into the center of a molten ball would appear to be a straightforward technique.

Further investigation, however, reveals several significant problems (ref. 15). Some of these, notably the problems of surface facets and dendritic growth during solidification under pure surface tension, are of considerable interest in crystallography. Stresses induced by density changes and uncertainties in centering the gas bubble may also lead to imperfections.

These potential problems might be avoided in various ways. For example, if rapid, homogeneous nucleation of fine crystals in the melt is achievable by supercooling, a smooth surface may result. The point is, that even the simplest appearing processes would require an extensive development program in zero-g.

REQUIREMENTS FOR A SPACE FACILITY

A materials and processes facility required on a manned station to explore some of these ideas can be described in general terms. Early experiments will probably involve levitation melting of refractory materials, crystal growing from the melt, vapor and solution, casting of composites, and studies of surface-tension-controlled shapes and processes. A compartment in a space station will be required to accommodate one or more men and the necessary apparatus. This will include an enclosed chamber, several feet in each dimension, with provision for inert gas flow, viewing ports and cameras, feed-throughs for motion and electrical inputs,

and an intense power source that may be supplied by radio-frequency-induction, an electron beam, or possibly focused solar radiation. A simple metallurgical microscope with specimen-treating equipment will also be desirable.

Experiments requiring an absolutely zero-g and vibration-free environment could be done in a chamber allowed to float free of the walls of the station for minutes up to hours. The same facility could accommodate certain experiments on the physical behavior of liquids, gases, and solids in zero-g.

CONCLUSIONS

An analysis of the influence that the space environment could exert on the processing of materials suggests that a materials laboratory would be a useful component of a space laboratory. A number of specialized materials have been identified as having unique properties that can probably be produced only under space conditions. The initial emphasis should be upon research to understand how materials behave during zero-g processing and to identify new materials and fabrication methods to be used later. It does not appear that early emphasis should be placed upon actual fabrication of specific products.

We believe that the materials presently proposed as candidates for study are limited by the abbreviated current state of knowledge. It is our expectation that experience with zero-g processing will markedly expand our horizons and generate a much broader spectrum of possibilities.

Development of new materials and processes puts a particular premium on the presence of man as a modifier and controller of the experimental conditions. The course of experiments will be determined by early results. Only a man on the scene, with apparatus under his control, can react and modify the next experiments as required.

Limitations on Zero-G

Earthbound simulations of zero-g are limited to periods of a few seconds in a drop tower or about 1 minute in an aircraft. Rockets can provide weightless intervals of several minutes, although these are necessarily preceded by periods of very high acceleration. Only in space can longer periods be achieved.

In an orbiting spacecraft, free-floating objects travel in independent trajectories, so that some restraining force will be required to avoid hitting the walls of the container. For example, without the restraining force, an object traveling in the orbital plane and placed 1 foot above and 1 foot in front of the center of gravity of the space station would describe the trajectory shown in figure H-1 (ref. 16), where X and Z refer to tangential and radial axes fixed in the space station. The average distance that such an object drifts along the X axis during one orbit is equal to $-12\pi Z_o$, where Z_o is the vertical distance from the center of gravity. The minus sign shows that, for positions above the X axis, the object is drifting backwards, while for positions below the X axis, the object moves forward. Note that the average drift distance per orbit is independent of the orbital altitude.

The acceleration required to alter an object's trajectory to maintain its position is very small (on the order of 10^{-7}g), and it is expected that the maximum accelerations will be those

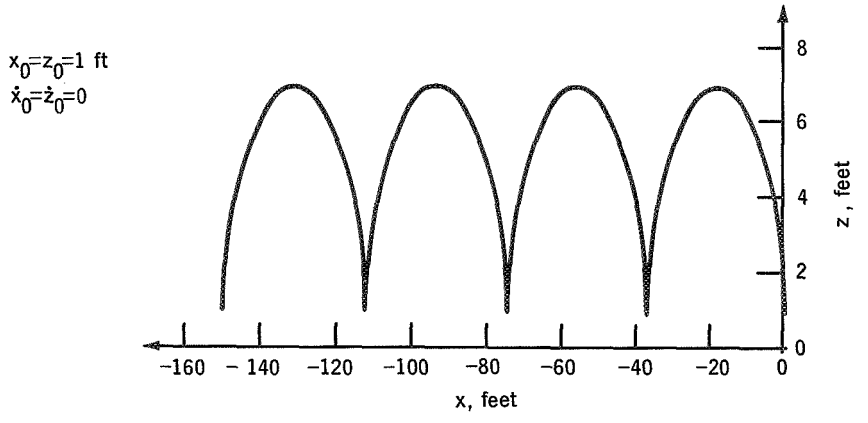

Figure H-1.–Typical trajectory of free-floating object (vertical plane).

caused by astronaut body motions, if thrusting is inhibited during these periods. Assuming that position-control accelerations of 10^{-3} to 10^{-4} g could be allowed during melting and casting operations, "rigid" position of a levitated mass relative to the spacecraft could be maintained despite the influence of astronaut body motions (ref. 9).

The influence of acceleration caused by positioning forces results in a shape distortion of the molten mass. For 10 kilograms of molten metal with a surface tension of 1000 dyne/cm and density of 8 gm/cc, the acceleration that causes its surface curvature to differ by a factor of 2 across the diameter is approximately 10^{-3} g. Rotation also causes distortion and, for the above 10-kilogram sample, a rotational period of a few seconds results in an oblate spheroid having a curvature at the equator twice that at the poles.

Lorentz forces will distort the floating fluid if eddy-current forces are used for position control or if radiofrequency fields are used for heating or stirring the specimen. Although the main limitations in radiofrequency levitation work will be removed, others will eventually be encountered because of potential failure of the integrity of a molten mass, if the processing of too large a batch is attempted.

The main disturbing forces will arise from the requirement for position control within the facility. Application of radiofrequency position-restoring forces will initiate shape oscillations in a molten mass. Because molten metals possess viscosity, such oscillations will diminish with time. The damping time is proportional to the square of the radius of the sphere and inversely proportional to the kinematic viscosity. For a 10-centimeter radius spherical mass of a density of 10 gm/cc and a viscosity of 2 to 4 centipoise, the time constant for damping will lie in the range of thousands of seconds. For spheres with radii near 1 centimeter, the damping times will be tens of seconds.

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